

A Survey of Planar Ultra-Wideband Antenna Designs and Their Applications

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Abstract— Recently, ultra-wideband (UWB) technology has attracted much attention both in the industry and academia due to its low cost, potential to handle high data rate and relatively low power requirement. A UWB antenna is one of the key components for realizing the UWB systems. We note, however, that designing a UWB antenna to deliver high performance is much more challenging than it is when dealing with the conventional narrowband antennas. Typically, it is desirable for a UWB antenna to cover a wide bandwidth spanning the entire range of 3.1-10.6GHz, to produce an omnidirectional radiation pattern, and to have a compact size as well as a simple configuration. This paper focuses on the design and analysis of planar printed UWB antennas, and provides some representative performance results of previously designed UWB antennas to illustrate the advantages as well as drawbacks of these antennas. Present state of development of UWB antennas is reviewed in the paper and some future trends of UWB antenna designs are presented. Furthermore, the topics of wideband enhancement techniques for UWB antennas, incorporating band-rejection characteristics and reconfigurability are addressed, and their application to cognitive radio communication systems is examined in-depth.

Index Terms— Ultra-wide band antenna, band-notched antenna, multi-band antenna, reconfigurable antenna, cognitive radio antenna, slot antenna, CPW-fed structure, microstrip-fed structure

I. INTRODUCTION

The use of ultra-wideband (UWB) technology can be traced back to the 1950s for military communications, and high-resolution radar [1-3]. UWB antennas are one of the key components needed to realize a UWB system, and a large number of UWB antennas have been designed and investigated in the past, both numerically and experimentally [4-11]. In particular, the Federal Communication Commission (FCC) has assigned the frequency band ranging from 3.1 GHz-10.6 GHz for commercial UWB communication applications [12], and a number of UWB devices have been

researched into and developed both in the industry and academia, including UWB antennas [13-15], UWB band-pass filters [16-17], and so on.

UWB technique is a radio transmission technology which occupies a relatively wide bandwidth, which exceed 500MHz as a minimum or it has at least 20% of the center frequency [18]. This technology has gained attention because of its potential as a novel approach for short-range and wide bandwidth wireless communication. In contrast to the traditional narrowband communication systems, UWB systems transmit information by generating radio energy at specific time instants in the form of very short pulses. Thus, these systems occupy a relatively large bandwidth and enable us to use time modulation. In addition, UWB systems can provide a high data rate which can reach up to hundreds of Mbits per second, and which make them useful for secure communication in military applications. Moreover, the UWB systems demand a relatively low transmitting power in comparison with the traditional narrowband communications systems; hence their use can prolong the battery life. In addition, use of short pulses helps reduce multipath channel fading since the reflected signals do not overlap with the original ones. In view of these aforementioned advantages, and following the approval of the FCC in 2002, a number of related topics pertaining to UWB systems have been proposed and studied for more than a decade.

One of the challenges associated with the implementation of UWB systems is the development of a suitable antenna that has a wide impedance bandwidth and an omnidirectional radiation pattern [19-22] over the entire frequency range of interest. Although many UWB antennas have been proposed to meet the requirements mentioned above [23-28], more often than not these antennas are relatively large in size, and this makes it difficult to integrate them into modern wireless devices. Printed antennas, which are small in size, have low profiles, and are easy to integrate with the hand-held terminals, have attracted much attention in recent years [29-33]. However, most of the proposed designs for these antennas suffer from narrow bandwidths, and a number of techniques have been proposed and investigated to render them suitable for UWB communication applications by enhancing their bandwidth [34-39]. One of the effective methods is to print a monopole antenna on a substrate fed by a

microstrip line. However, the microstrip feed is not easy to integrate with the microwave front end [40]. In view of this, a coplanar waveguide (CPW) has been adopted to reduce the integration complexity [41], and a number of CPW-fed UWB antennas have been proposed and investigated in recent years [41-49].

At this point it is worthwhile to note that there are several narrowband systems such as worldwide interoperability for microwave access (WiMAX), wireless local area network (WLAN), C- and X-band satellite communication systems, etc., whose operating frequency bands overlap with those of UWB systems. In order to mitigate the potential interference to the UWB systems from the narrowband systems alluded to above, the traditional method is to incorporate a band-stop filter into the antenna, though this increases the complexity of the devices and, hence, the cost [40]. Thus, designing an antenna with a band-rejection function is a desirable goal, which is albeit challenging. A number of non-planar UWB antennas with U-shaped slots introduced in their radiating elements have been proposed [50]. Although these antennas have good-band-notch characteristics, and are able to meet the requirements of UWB communication applications, their use are limited in these applications owing to their large size. To reduce the profile of these antennas, printed antennas have been widely studied for band-notch UWB applications [51-63]. A number of techniques have been proposed to realize the required band-notch functions, such as the U-slot [51], C-slot [53], L-slot [54], E-shaped slot [55], and the arc-shaped slot [56]. These slots are etched either on the radiating patch or in the ground plane. Consequently, they are prone to leak electromagnetic waves which either interfere with adjacent devices or with electronic components in the equipment. In addition, these leaking waves may also affect the radiation patterns of these UWB antennas. To improve the performance of these notch-band UWB antennas, an alternate approach which is based on the use of stubs has been proposed [64-65]. These stubs can be inserted into the ground plane or in the radiating patch to act as resonant filters. The drawback of this design is that it is difficult to insert the proper stub into the radiating patch of the microstrip-fed UWB antenna. Another flexible design, which utilizes a parasitic element technique has been investigated [66-70], and has been shown to possess good band-rejection characteristics as well as a relatively wide bandwidth. However, some of these designs require that the size of the antenna be increased. In other designs, the parasitic element is located on the opposite side of the radiating patch, which, in turn, increases its complexity. Recently, several designs that integrate band-stop filters into the feed line or the radiating patch of the antenna have been proposed [71-72]. The advantages of these band-notched UWB antennas are that their notch bands can be realized by devising corresponding filters. Additionally, these bands can be designed independently, which renders the design to be convenient. However, these notch-band antennas can only be used for notch-band type of UWB antennas, as is also the case for antennas described in [51-71].

Since standards for different generations co-exist in a

wireless network, the users demand a seamless handover among these standards when they move from one region covered by Global System for Mobile Communications (GSM) to another covered by Universal Mobile Telecommunications System (UMTS), and this in turn requires multi-mode wireless devices. At the same time, the wireless devices must offer a multi-band communication capability because each standard may operate within different frequency bands in specific regions of the world. Therefore, modern wireless devices must be multi-band and multi-mode and a UWB antenna which works equally well in multimode and multiband scenarios, becomes both attractive and desired, and it has been found that a reconfigurable design is a good candidate for meeting the requirements mentioned above [72]. In fact, reconfigurable techniques have been widely used in antenna designs, and have led to a number of reconfigurable UWB antennas proposed to realize integration of the UWB communication and band notch applications [72-87]. It is interesting to note that one of these reconfigurable UWB antennas can also be used for cognitive radio (CR) communications. In the CR communication systems, unlicensed users (secondary users) can access spectrum bands licensed to primary users in spectrum underlay or spectrum overlay modes. In the underlay mode, the secondary users are limited to a very low transmission power, which is less than -41.3 dBm/MHz for UWB users [76]. This can be realized by using impulse radio based UWB (IR-UWB) technology. For the overlay mode, the secondary users detect the existing narrow band (NB) signals, such as those from WLAN and RFID, and provide immunity to the NB systems. This can be implemented by turning off corresponding subcarriers in the orthogonal frequency division multiplexing UWB (OFDM-UWB), depending on the existence of primary users in a particular band [76, 87]. In other words, the transmission spectrum of UWB radios can be sculpted according to the presence of the primary users in the respective frequency bands in the environment [87]. Therefore, in CR-UWB systems, a CR antenna should cover the entire UWB band from 3.1 GHz to 10.6 GHz with no notch bands for underlay applications to detect the licensed primary users, and also provide immunity to these users by using band-notched technologies.

Unfortunately, the transmitted power of the UWB systems is limited to a relatively low level, namely under -41.3 dBm/MHz [12,88-90]. In order to overcome this limitation, the multiple-input and multiple-output (MIMO) technology using multipath has been combined with the UWB technology to find an alternative solution to the issues above [88-93]. However, another challenge in the implementation of the MIMO technique for compact devices arises from the presence of strong mutual coupling between the closely-packed antenna elements. Mutual coupling between the antennas can be usually improved by increasing the distance between the antenna elements but the compact size of the wireless devices makes it impossible to do so in most practical cases [88-89]. A possible approach appears to be to

enhance the isolation or to reduce the mutual coupling by using some other techniques, such as slots and stubs in the antenna structures.

This paper, which focuses on printed UWB antenna designs and applications, begins by presenting a review of the development of UWB antennas from past to present. First, we illustrate the UWB antenna designs based on microstrip-fed and CPW-fed techniques. Next, we describe the band-notched UWB antennas based on the previously proposed UWB antennas. Following this, we present some reconfigurable UWB antenna designs for multi-band and CR applications, and also introduce the concept of MIMO-UWB antennas. Finally, we turn to some special designs for configurable UWB antennas that have a wide bandwidth and notch-band reconfigurability, useful for multi-band as well as CR communication, which can meet the system requirements not only for UWB applications but for multi-band and CR communication applications as well.

II. CONVENTIONAL UWB ANTENNAS

As mentioned above, UWB technology is characterized by a large bandwidth that can be defined as absolute bandwidth and the fractional bandwidth. The FCC defines UWB operation as any transmission scheme that has a fractional bandwidth greater than or equal to 20% or an absolute bandwidth greater than or equal to 500 MHz. Here, the fractional bandwidth (FBW) is then given by the following equation:

$$FBW = 2 \frac{f_H - f_L}{f_H + f_L}, \quad (1)$$

where f_H is the upper boundary of the frequency bandwidth and f_L is the lower boundary of the frequency bandwidth. Many of the conventional wideband antennas, shown in Fig. 1, which satisfy the definition of UWB bandwidth, can be used for UWB applications. These conventional antennas include horn antennas, and monopole as well as dipole antennas, which have wide bandwidth and have been widely studied and investigated for UWB communication applications. However, these antennas are large in size, hence are difficult to integrate into hand-sets and indoor wireless communication terminals. In addition, their size cannot be significantly miniaturized in comparison with fully planar structures, such as microstrip antennas.

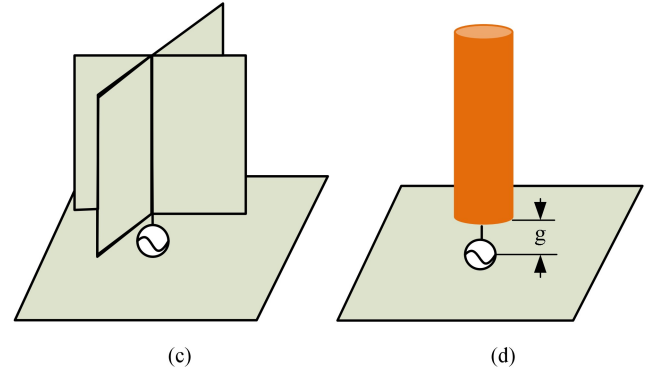
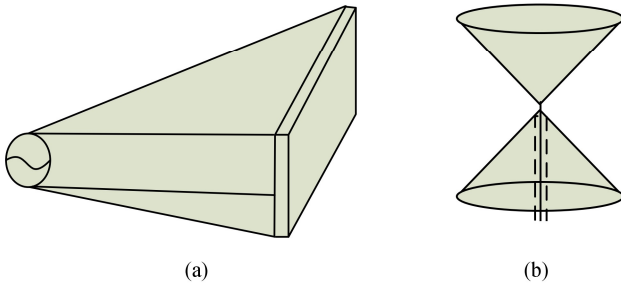


Fig.1 Conventional wideband antennas

III. PRINTED UWB ANTENNAS

A. UWB antennas

To meet the requirements for hand-held devices and indoor wireless applications, the monopole antenna shown in Fig. 1(d) has been modified to develop printed antennas by using the equivalent area method proposed in [29, 94-96], which is described below.

For a monopole antenna, the lower frequency f_L , with the voltage standing wave ratio (VSWR) less than 2, can be obtained by means of the approximation method of equivalent area from a cylindrical monopole antenna, shown in Fig. 2.

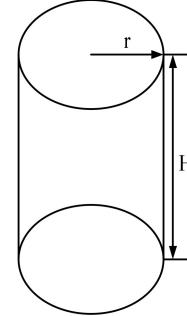


Fig.2 Parameters of cylindrical antenna shown in Fig. 1 (d)

The input real impedance of this antenna when the length of the monopole is slightly smaller than that of a thin-wire monopole and is given by (2)

$$H = 0.24 \lambda f, \quad (2)$$

where H is the height of the monopole radiation element of Fig. 1(d), which is also shown in Fig. 2, and λ is the wavelength. Here, f is given by

$$f = \frac{\frac{H}{r}}{1 + \frac{H}{r}} = \frac{H}{H + r}. \quad (3)$$

From (2) and (3), we can find the expression of the wavelength λ as follows:

$$\lambda = \frac{H}{0.24 f} = \frac{H}{0.24 \frac{H}{H + r}} = \frac{(H + r)}{0.24}. \quad (4)$$

Thus, the lower frequency f_L is given by

$$f_L = \frac{c}{\lambda} = \frac{300 \times 0.24}{H+r} = \frac{72}{H+r}, \quad (5)$$

where c is the velocity of light. By including the effects of the probe length of the non-planar monopole antenna, shown in Fig. 1(d), (5) can be modified to:

$$f_L = \frac{72}{H+r+g}, \quad (6)$$

where g is the length of the probe and the parameters H , r and g are in millimeters. For the cylinder, we have

$$2\pi \times r \times H = S, \quad (7)$$

where S is the surface area of the cylinder. For the rectangular printed monopole antenna, the area of the radiating element is given by:

$$S = W \times H, \quad (8)$$

where W is the width of the radiating patch. Thus, we have

$$r = \frac{W}{2\pi}. \quad (9)$$

Based on this approximation technique for designing printed monopole antennas, various monopole UWB antennas, shown in Fig. 3, have been proposed and widely studied. The approximation theory given above has been used to derive the original dimensions of the rectangular, circular, triangular and polygonal type of patch [29, 95] antennas. From the simulation results described in [95], we can see that the circular patch monopole antennas exhibit the best impedance bandwidth. However, these microstrip-fed UWB antennas are printed on both sides of the substrate, which not only increases the cost of the antenna design but also renders them difficult to integrate with the radio frequency front-end.

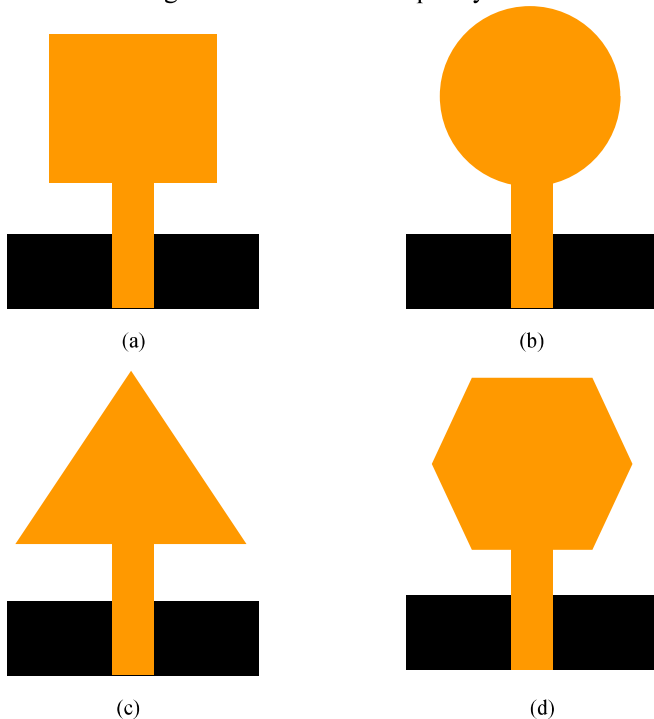


Fig.3 Microstrip-fed monopole antennas for UWB applications (yellow part

is the fed line and the radiating patch, while the black part is the ground plane).

A number of CPW-fed UWB antennas with compact size have been developed and investigated to meet the requirements of impedance bandwidth and the omnidirectional radiation pattern characteristics [41-49]. Examples are the circular and square patch UWB antennas shown in Fig. 4. Note that these CPW-fed UWB antennas are printed only on one side of the substrate, which may reduce the cost of fabrication. Moreover, the CPW-fed structure is easy to integrate with the front-ends of wireless communication systems, which not only simplifies the design of the front-end but also gives rise to low complexity of the device. From the previous investigations on the design of CPW-fed UWB monopole antennas, we know that these antennas are compact in size, and they offer a wide bandwidth, as well as good omnidirectional radiation patterns that are suitable for practical UWB communication applications.

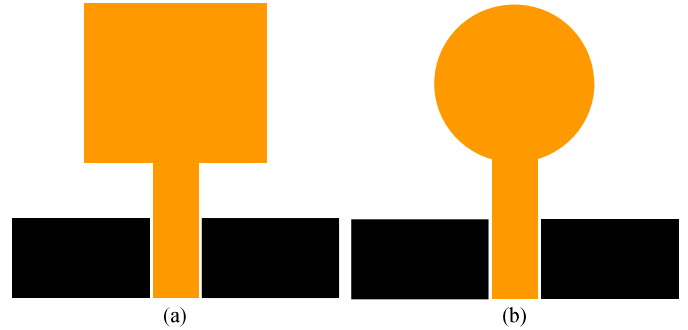


Fig.4 CPW-fed monopole antennas for UWB applications (Yellow part is the feed line and the radiation patch, while the black part is the ground plane).

B. Bandwidth Enhancement Techniques

We point out that some of the proposed UWB antennas cannot cover the entire impedance bandwidth designated by the FCC, which ranges from 3.1 GHz to 10.6 GHz. In order to enhance the impedance bandwidth of these antennas, several bandwidth enhancement techniques have been proposed. These include introducing stair-case tapers on the radiating patch, or inserting slots either on the radiating patch or in the ground plane of these UWB antennas [34-39, 97-98], as shown in the examples presented in shown in Fig. 5. By using these bandwidth enhancement techniques, the impedance bandwidth of the related antennas can be significantly improved.

Some alternate designs of microstrip-fed wide slot antennas can also achieve the wide impedance bandwidth designated by the FCC. In addition, motivated by the bandwidth enhancement concepts mentioned above, microstrip-fed wide slot UWB antennas with bandwidth enhancements, shown in Fig. 6 as examples, have been proposed to improve the bandwidth of these wide slot antennas [99-100]. However, these designs do not match the advantages of the CPW-fed techniques. And, consequently, a variety of wide slot antennas fed by CPW, which have radiating patches of different shapes, have been proposed and

investigated for UWB communication applications [41-49].

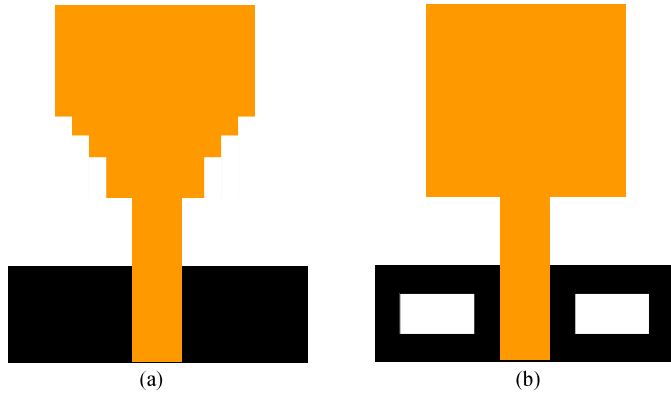


Fig.5 Bandwidth enhancement for UWB antenna designs (Yellow part is the feed line and the radiating patch, while the black part is the ground plane)

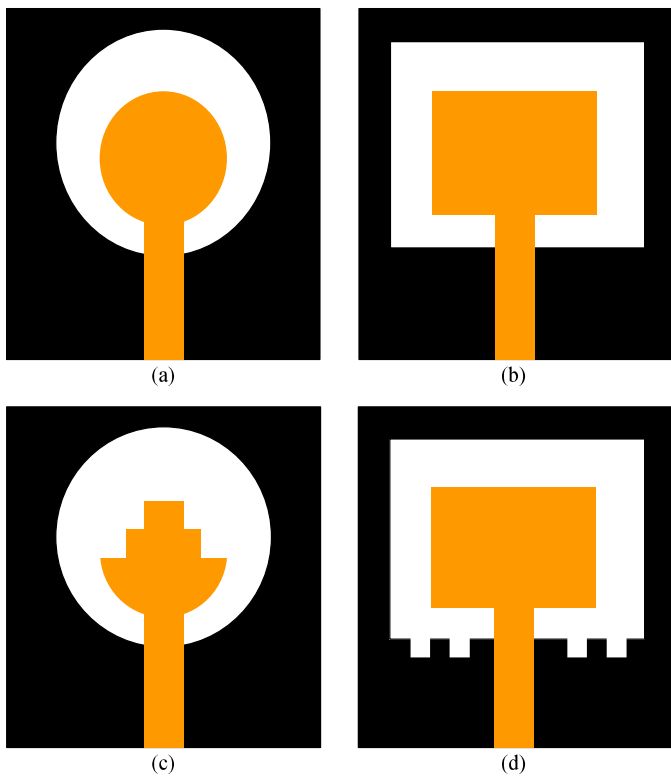


Fig.6 Microstrip-fed wide slot UWB antennas and bandwidth enhancement techniques (Yellow part is the feed line and the radiating patch, while the black part is the ground plane)

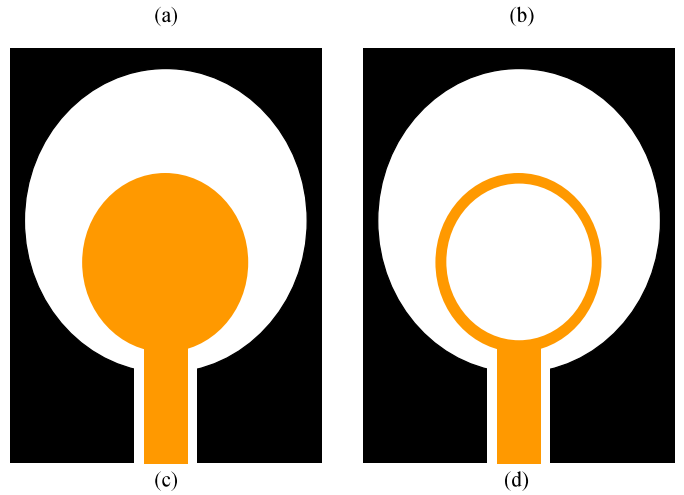
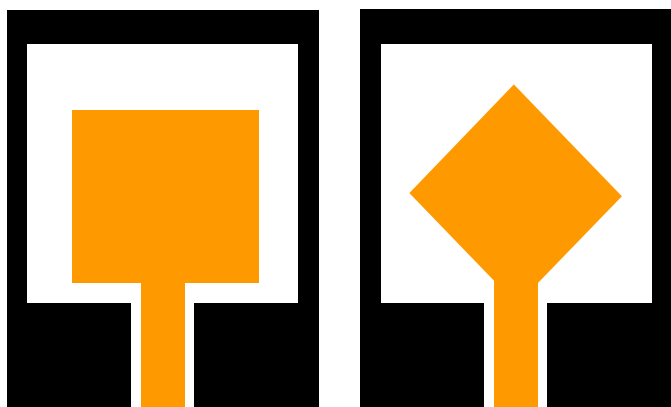


Fig.7 CPW-fed wide slot UWB antennas (Yellow part is the feed line and the radiating patch, while the black part is the ground plane).

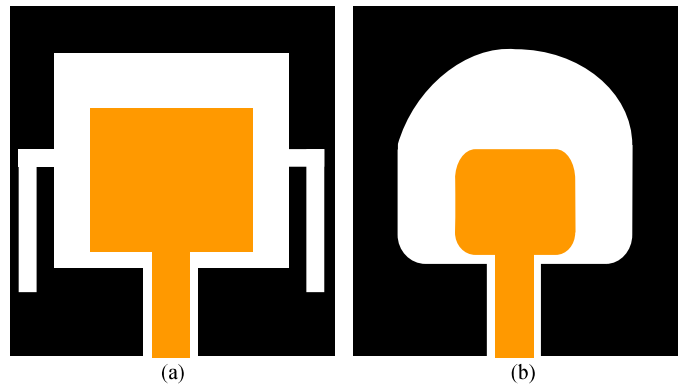


Fig.8 Bandwidth enhancement of CPW-fed wide slot UWB antennas (Yellow part is the feed line and the radiating patch, while the black part is the ground plane)

In addition, corresponding bandwidth enhancement methods have also been integrated into these CPW-fed wide slot UWB antennas to broaden their bandwidths [36-38]. These configurations of CPW-fed UWB antennas are shown in Figs. 7 and 8.

C. Band-notched UWB antennas

Based on the above discussion of microstrip- and CPW-fed UWB antennas, we observe that these UWB antennas not only cover the entire bandwidth designated by the FCC, but can also provide good radiation patterns over the operational frequency band. However, there exist a large number of narrowband wireless communication systems that have around for a long time, and they may present potential interference with the UWB system and *vice versa*. Examples are IEEE 802.11a WLAN systems operating at 5.15–5.825 GHz, super high frequency (SHF) and satellite services operating in the 4.5-5 GHz band, IEEE 802.16 WiMAX systems operating in 3.3–3.7 GHz range and ITU 8 GHz band operating in the 7.725-8.275 GHz band. To suppress these types of unwanted potential interference to the UWB system, the traditional method is to insert narrowband band-stop filters in the antenna or in the feed line, which increases the complexity as well as cost of the devices. Thus, it is

worthwhile to investigate the design of UWB antennas with filtering characteristics or notch-band functions, and realize compact implementations of the same. Inserting various slots, either on the radiating patch or on the ground plane, may be one of the most simple, effective, and inexpensive methods to achieve the desirable goals stated above.

Alternatively, a number of strategies have been proposed to address the band-notch problem by introducing slots of different shapes, either in the radiating patches or in the ground planes [51-63, 101]. Typical slot shapes are: rectangular, C-shaped, pi-shaped, E-shaped, H-shaped and U-shape slots. In addition, combining the C-shaped slot with the U-shaped resonators is also a viable approach to providing improved filtering function. The disadvantage of these etched slots is that they may leak electromagnetic waves, which, in turn will adversely affect the radiation patterns. Thus, some band-notched UWB antennas are realized by using stubs [64-65] and parasitic elements [66-70] instead of slots.

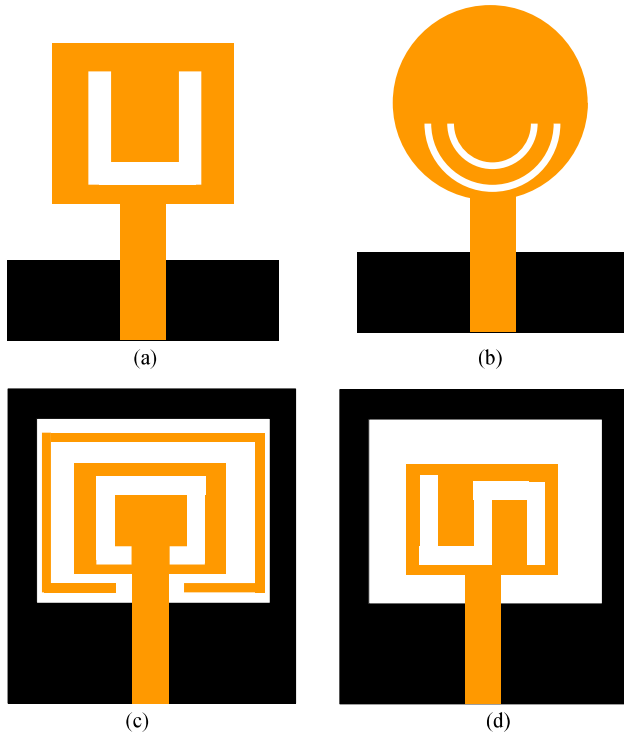


Fig.9 Microstrip-fed wide slot UWB antennas (Yellow part is the feed line and the radiating patch, while the black part is the ground plane)

Several examples of notch-band UWB antennas with CPW and microstrip feeds are shown in Figs. 9 and 10. These notch-band UWB antennas either have a single or dual notch-band, which can effectively suppress the potential interference between the UWB and other narrowband systems.

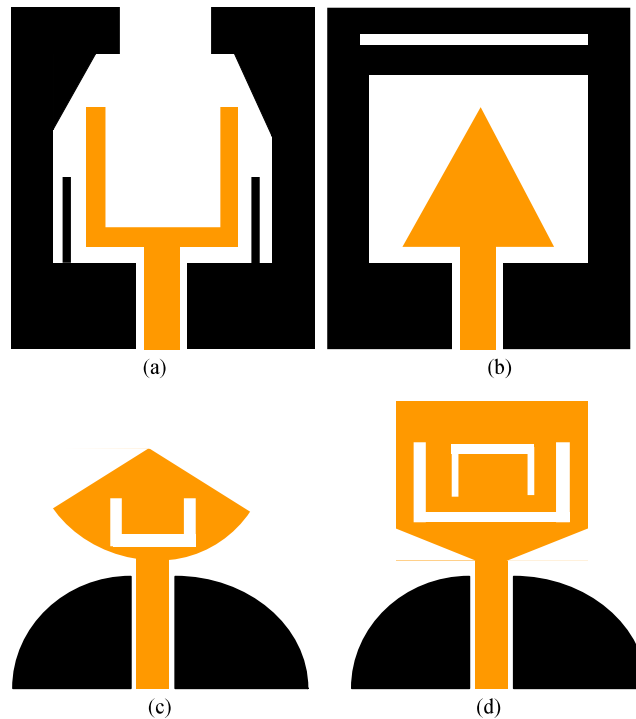


Fig.10 CPW-fed wide slot UWB antennas (Yellow part is the feed line and the radiating patch, while the black part is the ground plane)

D. Reconfigurable UWB antennas

It is worthwhile to mention that these band-notched UWB antennas cannot be used to cover the entire UWB band we desire. Thus, designing a UWB antenna which can switch between a notch-band and a conventional UWB antenna is necessary. For this reason, a number of reconfigurable UWB antennas have been proposed for operation either as a notch-band or a full UWB antenna, an example being the reconfigurable wide slot UWB antenna shown in Fig.11. In this figure, switch-1 (SW1), switch-2 (SW2) and switch-3 (SW3) are used for controlling the operational state of the UWB antenna [102]. When all the switches are turned ON, this antenna operates as a band-notched UWB antenna, which can be used to reduce potential interference from signals emanating from narrowband systems. When all the switches are OFF, this antenna functions as a UWB antenna, which covers the entire the FCC-designated UWB band ranging from 3.1 GHz to 10.6 GHz. However, when the SW1 switch is ON while SW2 and SW3 are OFF, it functions as a UWB antenna with only a single notch band. In this design, the SW2 and SW3 are turned ON or OFF at the same time to retain the symmetry of the antenna, which can also achieve a good omnidirectional radiation pattern. In addition, such reconfigurable UWB antennas can also be used for UWB-CR communication applications. Thus, the reconfigurable UWB antenna is one of the desirable candidates for such applications [72-87].

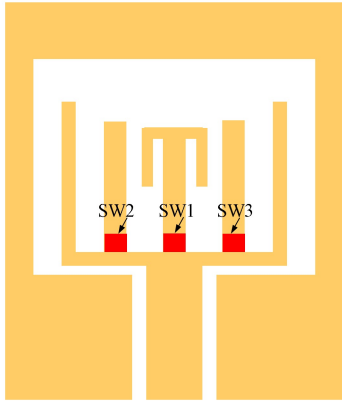
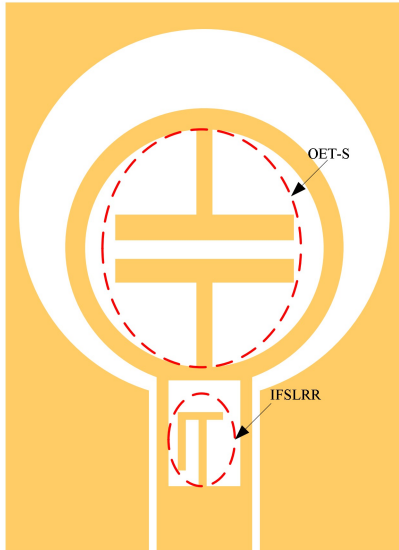


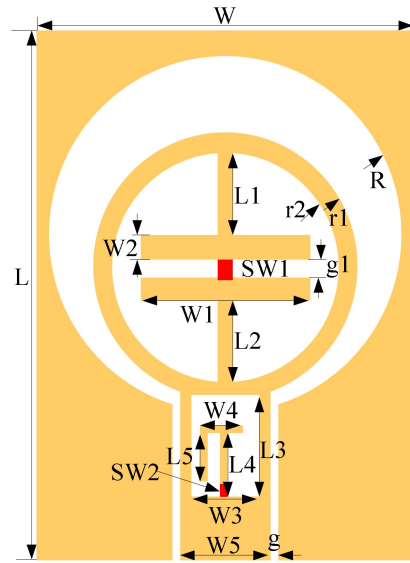
Fig.11 Reconfigurable band-notched UWB antenna

IV. SPECIAL DESIGN OF RECONFIGURABLE UWB ANTENNAS

We now turn to an example of a reconfigurable UWB antenna design, which is a modification of the reconfigurable UWB antenna described in [103]. The geometry of the proposed reconfigurable dual-band-notched UWB antenna is presented in Fig. 12. A substrate with a dielectric constant of 2.65, a loss tangent of 0.002, and a thickness of 1.6mm is employed to design the antenna by using a commercial electromagnetic solver HFSS (High Frequency Structure Simulator) based on the Finite Element Method (FEM). The antenna consists of a circular wide-slot in the CPW ground plane, a circular ring radiating patch, a pair of open-ended T-shaped stubs (OET-S) inserted into the inside of the circular ring radiating patch, an inverted-F stub loaded rectangular

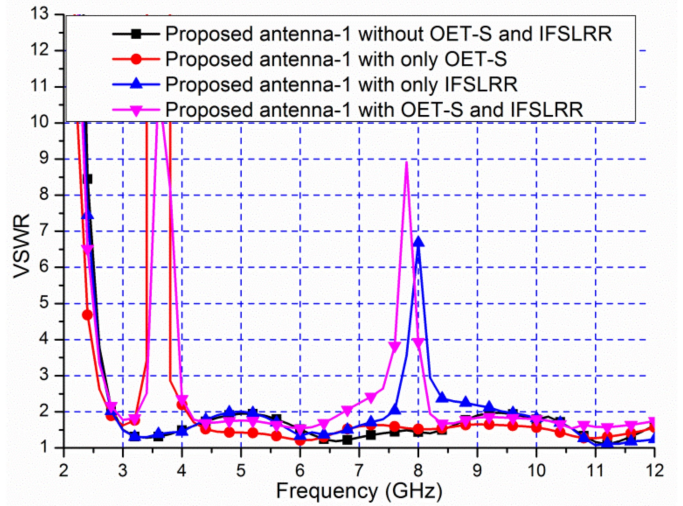


(a) antenna-1

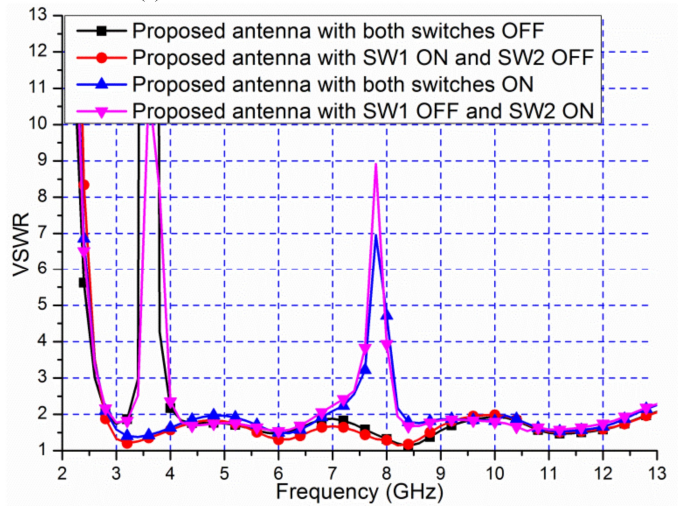


(b) antenna-2

Fig.12 Example of a reconfigurable UWB antenna



(a) Band-notched characteristic of the antenna



(b) Reconfigurable characteristic of the antenna

Fig.13 Performance of the proposed antenna in Fig.12.

resonator (IFSLRR) etched in the CPW-fed transmission line, two ideal switches denoted as switch-1 (SW1) and switch-2 (SW2), and a CPW ground plane together with a 50 Ohm CPW feed structure. The 50 Ohm CPW feed structure is comprised of two parts, namely, CWP-fed transmission line having a width of $W_5=3.6\text{mm}$ and a gap between the CPW ground plane, and the CWP-fed transmission line with a width of 0.2mm . The detailed parameters of the reconfigurable UWB antenna is listed as follows: $L=32\text{mm}$, $W=24\text{mm}$, $R=11.6\text{mm}$, $r_1=6.6\text{mm}$, $r_2=5.1\text{mm}$, $L_1=4.1\text{mm}$, $W_1=6.5\text{mm}$, $L_2=4.1\text{mm}$, $W_2=0.7\text{mm}$, $L_3=5\text{mm}$, $W_3=2.7\text{mm}$, $L_4=3.6\text{mm}$, $L_5=1.9\text{mm}$, $W_4=1.55\text{mm}$, $W_5=3.6\text{mm}$, $g=0.2\text{mm}$, $g_1=0.6\text{mm}$.

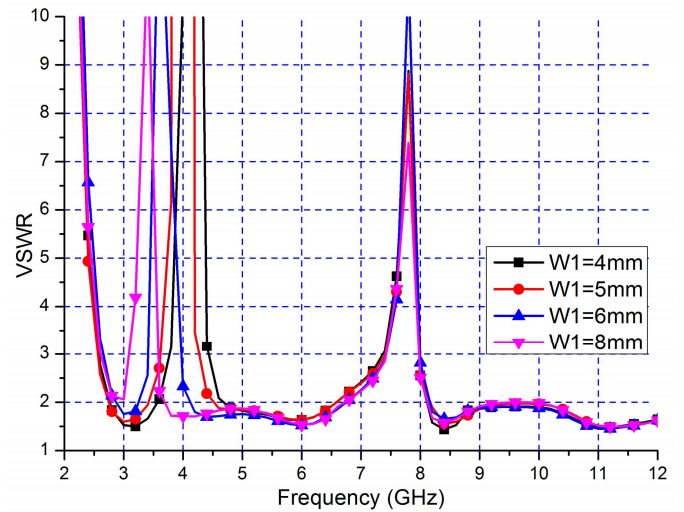
To study the effects of OET-S, IFSLRR, and switches on the performance of antenna structure in Fig. 12, two scenarios are considered: (i) antenna-1 with no switches and (ii) antenna-2 with switches. Fig.13 (a) shows the band-notch characteristics of the proposed antenna-1. It is found that in the absence of OET-S and the IFSLRR, the proposed antenna functions as a UWB antenna, with an impedance bandwidth of 9.3 GHz ranging from 2.7 GHz to 12 GHz; hence it covers the entire UWB band from 3.1 GHz to 10.6 GHz designated by the FCC. The proposed antenna-1, with just the OET-S, is a UWB antenna with a single notch-band located at the 3.5 GHz WiMAX band. The center frequency of the notch band can be tuned by adjusting the dimensions of the OET-S. On the other hand, the proposed antenna-1, with only the IFSLRR inserted in the CPW-fed transmission line, is a band-notched UWB antenna whose notch is near 8GHz, which can prevent the potential interference from X-band signals near that frequency. Finally, the proposed antenna-1, containing both the OET-S and the IFSLRR, is a dual band-notch UWB antenna. The two notch-bands are located at 3.5 GHz WiMAX band and the 8 GHz X-band, respectively, which can be used for mitigating the problem of interference from these narrow-band systems. We can summarize this discussion by saying that the notch band at 3.5 GHz WiMAX is generated by using the OET-S, while the X-band notch is realized by the IFSLRR. The reconfigurable characteristics of the proposed antenna-2 are shown in Fig. 13 (b). For the purpose of the simulation, we have assumed that the presence of a metal bridge represents the ON state, while its absence represents the OFF state [72-73, 75-76, 82]. To implement the ON state of SW1, a strip-line with a length of 0.8mm and width of 0.6mm is employed for the SW1, while a strip-line with dimensions of $0.3\text{mm}\times 0.5\text{mm}$ is used for SW2 to design the ON state. It is found that the antenna-2 with both switches OFF functions as a band-notched UWB antenna with the notch located at 3.5 GHz WiMAX frequency. With SW1 ON and SW2 OFF, the antenna-2 operates as a UWB antenna covering the bandwidth from 2.7 GHz to 12 GHz. With both the switches ON, the antenna-2 becomes a UWB antenna with a single notch-band in the X-band that enhances the immunity of the UWB antenna from radar interference.

Turning now to the antenna-2, it operates as a UWB antenna with SW1 OFF and SW2 ON, with two stop bands at

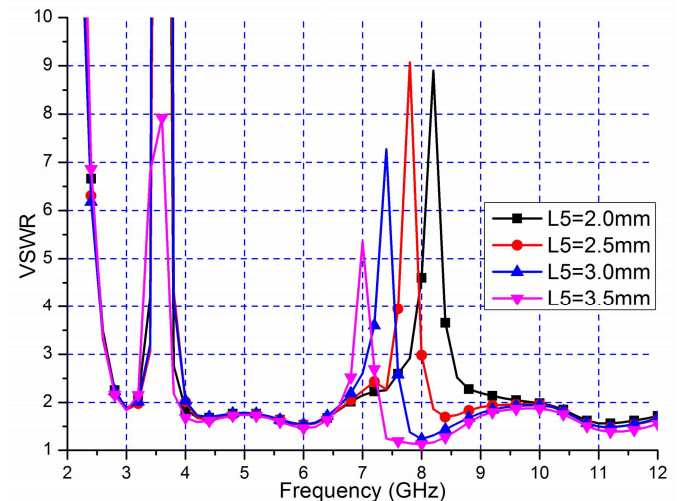
3.5 GHz WiMAX and 8 GHz X-band, respectively. By controlling the switching states, namely ON and OFF, the proposed antenna can be used either as a dual or a single band-notch UWB antenna, or even as a conventional UWB antenna. It can also be used as a multi-band antenna with both switches ON and OFF, or with SW1 OFF and SW2 ON.

To better understand the functionality of the controllable band-notch characteristics of the proposed antenna, the parameters W_1 and L_5 are selected to illustrate the wide tunable notch-band characteristics with the SW1 OFF and SW2 ON. The simulated results are shown in Fig.14. The effects of varying W_1 are illustrated in Fig.14 (a). We observe that the lower notch-band shifts to the lower frequencies as we increase W_1 , because changing W_1 alters the resonance and, hence, the notch-band. Thus, the center frequency of the lower notch-band moves to lower frequencies.

The effect of varying the length of L_5 is shown in Fig. 14 (b). It is found that the higher notch band moves to lower frequencies with an increasing of the L_5 . Changing L_5 alters the current length of the inverted-F stub, and hence the resonance frequency of the higher notch band moves to low



(a) VSWR with varying W_1



(b) VSWR with varying L_5

Fig.14 Parasitic variation of the proposed antenna

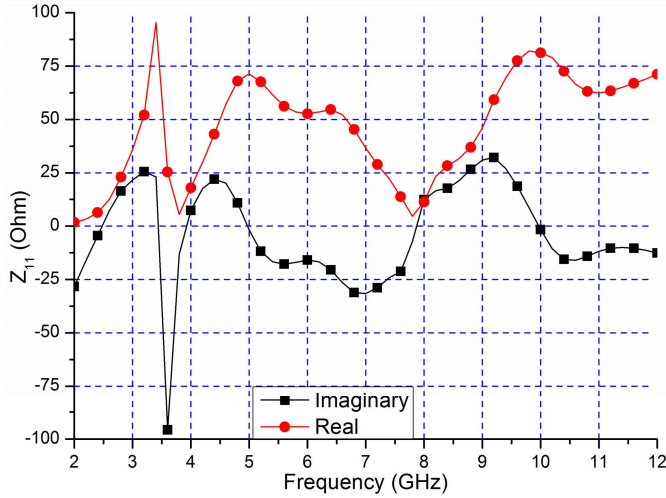
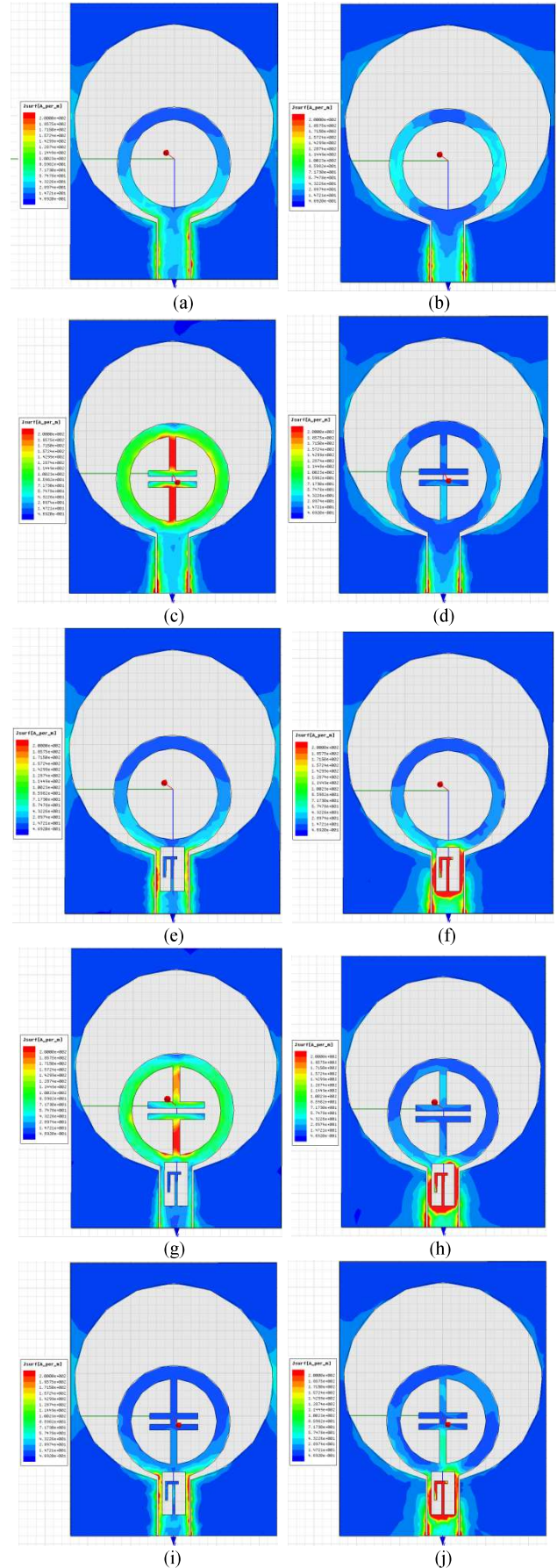


Fig.15 Impedance characteristic of the proposed antenna with SW1 OFF and SW2 ON

frequencies. The impedance of the proposed antenna with the SW1 OFF and SW2 ON is described in Fig. 15. It is found that the real part of Z_{11} drops to near zero at the 3.8 GHz WiMAX band and near 8GHz at the X-band, which helps suppress the resonances at these two bands. Thus, the two notch bands are generated at these non-resonance frequencies by using this approach.

To further study the performance of the proposed antenna, the current distribution of the antenna is investigated and shown in Fig.16. In this simulation, Figs. 16(a)-(f) are the design procedure of antenna-1 and the current distributions are investigated at 3.6 and 7.8 GHz. Figs. 16(a) and (b) show the current distribution of antenna-1 without OET-S and IFSLRR. It can be seen that the current mainly flows through the CPW-fed structure and through the circular ring radiating patch. Figs. 16(c) and (d) show the current of the antenna-1 with only OET-S. It can be seen that the current at the 3.6 GHz is concentrated on the OET-S, while the current at 7.8 GHz mainly flows through the CPW-fed structure, edges of the circular slot, and the circular ring radiation patch. Thus, the lower notch band is generated by the OET-S. Figs. 16(e) and (f) show the current with only IFSLRR. It can be seen from these two figures that the current flows on the CPW-feed structure and the circular ring radiating patch at 3.6 GHz. Also, the current at 7.8 GHz is mainly concentrated on the inverted-F stub. Hence, the higher notch-band is given by the IFSLRR. Figs. 16(g) and (h) illustrate the current density distribution of the proposed antenna-1 with both OET-S and IFSLRR. We can see from Figs. 16(g) and (h) that the current at the lower notch band is concentrated on the OET-S and at the higher notch band on the IFSLRR. Thus, the two notch bands are obtained by the OET-S and IFSLRR, respectively.



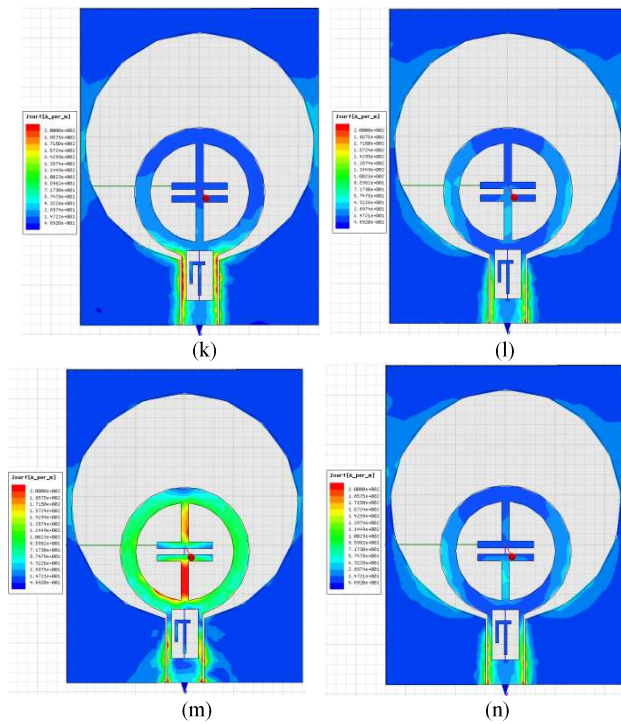


Fig.16 Current density distribution of the proposed antenna

Figs. 16(i) and (j) show the proposed antenna-2 with both switches ON. The current at the lower notch-band flows along the CPW-feed structure and in the circular ring-shaped radiating patch, while the current at the higher notch-band still concentrates on the IFSLRR, causing the lower notch to disappear. In this case, the antenna is also operated as a UWB antenna with a notch at 7.8 GHz, which can be used to reduce the potential interference from the X-band. The current distributions for the case of the antenna with SW1 ON and SW2 OFF are shown in Figs. 16(k) and (l), respectively. We can see that at both the bands the current flows mainly through the CPW-feed structure and the circular ring radiating patch, causing the two notch bands to disappear, and the proposed antenna functions as an UWB antenna. Figs. 16(m) and (n) show the current distributions when both of switches are OFF. In this case, the current distribution in the lower notch-band concentrates in the OET-S. The currents at the higher notch-band flow through CPW-feed structure and the circular ring radiating patch, and the higher notch-band disappears. In this case, the antenna operates as a UWB antenna with a notch in the 3.5 GHz WIMAX band. Thus, the proposed antenna can be used as a dual band-notched UWB antenna, or a single notch band UWB antenna, or even a UWB antenna, by controlling the switch states ON or OFF. The radiation patterns of the proposed antenna for the cases of either both of the switches ON or OFF at 3.2 GHz and 7 GHz have been investigated, and are shown in Fig. 17. It is worthwhile to point out that the radiation patterns of the reconfigurable antennas are omni-directional in the H-plane and are dipole-like in the E-plane.

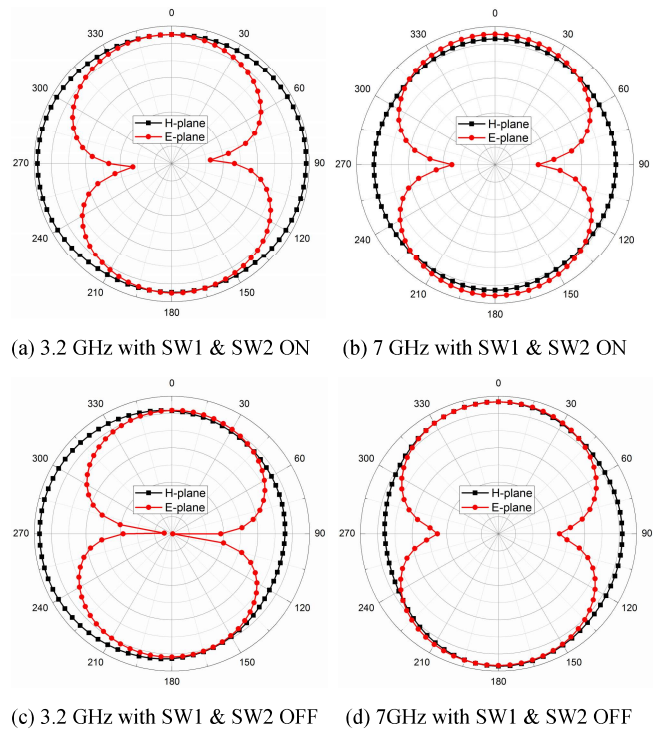


Fig.17 Simulated radiation patterns

FUTURE WORK AND DEVELOPMENT

Since the 3.1-10.6 GHz bandwidth has now been released for commercial applications, some topics are still being investigated for future UWB antenna designs. These are:

1. Multiple notch band UWB antennas

As pointed out above, a large number of narrowband systems have been used in the past, either for personal applications or for the military. Thus, designing a UWB antenna with additional notch-bands is desired, example being triple and quintuple band-notched UWB antennas. To design a compact UWB antenna, it may be necessary to consider new designs for band-notched UWB antennas, which combine several of the proposed band-notched design techniques that may be found in [104-108].

2. Reconfigurable UWB antennas

Designing reconfigurable UWB antennas to be used in both the narrowband and UWB systems should be further investigated to best utilize the limited spectrum resources [109-114]. At the same time, further use of MEMS or PIN diodes should be explored to develop UWB antennas for cognitive radio applications. In addition, active UWB antenna design may be another topic for future reconfigurable UWB antennas, which would entail the implementation of non-foster impedance wideband matching techniques [115].

3. MIMO UWB antennas

Since the UWB antennas have wide bandwidths, designing UWB-MIMO antennas to improve the performance of UWB systems and to reduce the mutual coupling should be investigated. Existing MIMO antenna design techniques may be revisited and modified for UWB-MIMO antenna applications [88-93].

4. UWB antennas applications

Since UWB system has a wide bandwidth and is designed for transmitting pulses, the UWB communication technology can be used in agriculture for temperature and humidity monitoring in the winter; breast tumor detection [116]; radar communication; emergency services; on-body communication applications [117-119]; and so on.

V. CONCLUSIONS

In this paper, we have reviewed a wide variety of UWB antennas and have found that there are several interesting aspects that need to be taken into account when designing high performance UWB antennas, as opposed to conventional narrowband antennas. We have pointed out a number of potential applications that could be further considered for designing UWB antennas. We have recognized that UWB antenna measurements and characterization of UWB antennas for practical applications should be carried out in the time domain. Looking into the future, we believe that UWB antennas show considerable promise and that they will witness further developments alongside the rapid and explosive growth of wireless communication technology that we are witnessing today.

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Editorial Comment

A quick survey of antenna-related literature clearly shows that there is considerable research activity in the area of Ultra-wideband (UWB) antenna design—both with and without the capability of interference suppression—realized by using notches in the frequency response characteristics. The contribution by Yingsong presents a survey of a variety of antenna design strategies for covering the wide frequency band designated as UWB by the FCC, and for suppressing certain interference frequencies that fall within this band.
